An Efficient Implementation of Automatic Cloud Cover Assessment (ACCA) on a Reconfigurable Computer

Esam El-Araby[1], Mohamed Taher[1],

Tarek El-Ghazawi[1], and Jacqueline Le Moigne[2]

[1]George Washington University

[2]NASA Goddard Space Flight Center (GSFC)

Outline

- Objectives
- Introduction and Background
  - Cloud Detection Theory
  - Cloud Detection Algorithms
- Implementation Approach
  - Architectural Modules
  - Testbed (SRC-6)
- Experimental Results
  - Measurements Scenarios
  - Detection Accuracy
  - Performance
- Concluding Remarks
- References

Objectives

◆ Remote Sensing On-Board Processing?

- Data, **aboard the carrier**, is pre-processed and selected to be transmitted, to Earth stations
- **Simpler and faster** subsequent computations
- Reduces the **cost and the complexity of the On-The-Ground/Earth processing system**
- Enables **autonomous decisions to be taken on-board → faster critical decisions**
- Reduction of **communication bandwidth**
- Example Pre-Processing operations: **Dimension Reduction** (PCA-, Wavelet- based), **Cloud Detection**

◆ Reconfigurable Computers?

- Parallel systems designed around multiple general-purpose processors and multiple FPGA chips to provide low-level hardware functionality at the same level of programmability as general-purpose computers
- **Higher performance** (throughput and processing power) compared to conventional processors
- **Lower form / wrap factors** compared to parallel computers
- **Higher flexibility** (reconfigurability) compared to ASICs
- **Less costs and shorter time-to-solution** compared to ASICs

◆ Cloud Detection?

- A critical role in **weather- and climate-related studies**
- A **source of errors** that can hinder the use of satellite data in many applications such as land-cover / land-use

Purpose & Operational Procedure

- The Landsat Processing System performs cloud cover assessment on every image prior to archiving
- Cloud cover scores (percentages) are tabulated and reported on a quarter scene and full scene basis
- Cloud cover scores are recorded in scene metadata records
- Cloud cover scores are reviewed daily by the Mission Operations Center to determine image acquisition success or failure (based on long term acquisition plan criteria)
- Cloud cover scores are available to users for identifying candidate imagery

Outline

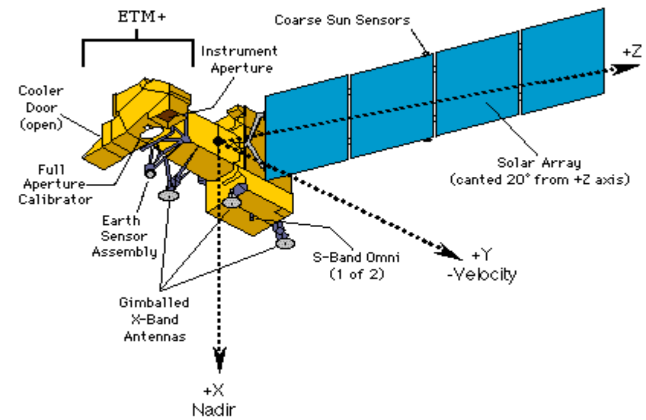
- Objectives
- **Introduction and Background**
  - **Cloud Detection Theory**
  - **Cloud Detection Algorithms**
- Implementation Approach
  - Architectural Modules
  - Testbed (SRC-6)
- Experimental Results
  - Measurements Scenarios
  - Detection Accuracy
  - Performance
- Concluding Remarks
- References

Cloud Detection Theory

- **Theory is based on the observation that clouds are:**
  - **Highly reflective (in the visible, near- and mid- IR bands)**
    - **Band2 (Green band ≡ 0.52 - 0.60 μm)**
      - Measures green reflectance
      - Vegetation discrimination
    - **Band3 (Red band ≡ 0.63 - 0.69 μm)**
      - Measures Chlorophyll absorption
      - Plant Species differentiation
      - Combined with Band2 shows land surface as red-like
    - **Band4 (Near-IR band ≡ 0.76 - 0.90 μm)**
      - Determines soil moisture level
      - Delineating water bodies and distinguishing vegetation types
      - B4/B3 is constant (≈1) over clouds and varies over water and vegetation
    - **Band5 (Mid-IR band ≡ 1.55 - 1.75 μm)**
      - Supplies information about vegetation and soil moisture
      - Differentiation of snow from clouds
  - **Cold (in the thermal bands)**
    - **Band6 (Thermal IR band ≡ 10.4 - 12.5 μm)**
      - Thermal mapping to Brightness Temperatures
      - Difference between 11 μm & 12 μm highlights cloud boundaries

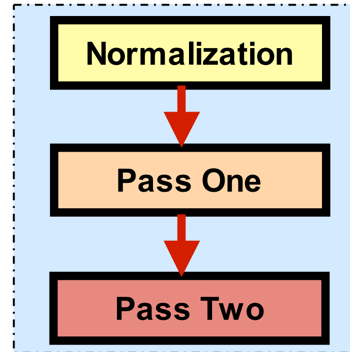
Cloud Detection Algorithms

- **Algorithms**
  - **Landsat 4 & 5 ACCA**
    - **Threshold based - 3 filters**
    - **Trouble with cold, highly reflective landscapes (e.g. tundra, deserts)**
    - **Imperfect snow/cloud discriminator**
    - **Insensitive to warm clouds**
    - **Performance suffers at low sun elevation angles**
  - **MODIS (Moderate Resolution Imaging Spectroradiometer)**
    - **Threshold based - 13 filters**
    - **Parameters differ depending on the time of day and the pixel ecosystem**
    - **Supporting ecosystem maps and land/sea masks are required**
  - **Landsat 7 ETM+ (Enhanced Thematic Mapper) ACCA**
    - **Threshold based - 8 filters**
    - **A compromise between Landsat 4&5 and MODIS**
    - **Two-pass approach**
      - Pass one → Fixed thresholds
      - Pass two → Adaptive thresholds based on statistical analysis of pass one results



Landsat 7 Satellite

Landsat 7 ETM+ ACCA
(Algorithm Outline)



- **Normalization**
  - ETM bands 2-5 (Reflectance bands)
    - Correction for illumination (solar zenith) angle → reflectance (ρ)
  - Band 6 (Thermal band)
    - Calibrated to an equivalent blackbody Brightness Temperature
- **Pass One**
  - Identifies clouds (produces Cloud Mask)
  - Minimizes errors of commission

	Filter	Function
1	**Brightness Threshold** $B_3 > 0.08$	Eliminates dark images
2	**Normalized Difference Snow Index (NDSI)** $NDSI = \frac{B_2 - B_5}{B_2 + B_5} < 0.7$	Eliminates many types of snow
3	**Temperature Threshold** $B_6 < 300K$	Eliminates warm image features
4	**Band 5/6 Composite** $(1 - B_5)B_6 < 225$	Eliminates numerous categories including ice
5	**Band 4/3 ratio** $\frac{B_4}{B_3} < 2$	Eliminates bright vegetation and soil
6	**Band 4/2 ratio** $\frac{B_4}{B_2} < 2$	Eliminates ambiguous features
7	**Band 4/5 ratio** $\frac{B_4}{B_5} > 1$	Eliminates rocks and desert
8	**Band 5/6 Composite** $(1 - B_5)B_6 > 210 \Rightarrow warm\ \ clouds$ $(1 - B_5)B_6 < 210 \Rightarrow cold\ \ clouds$	Distinguishes warm clouds from cold clouds

Classification	Rule
Snow	$\left(NSDI = \frac{B_2 - B_5}{B_2 + B_5} > 0.7\right)\ AND\ (B_4 > 0.1)^A$
Desert	$\frac{B_4}{B_5} < 0.83^B$
NotCloud	$(B_3 < 0.08)\ OR\ (B_6 > 300)\ OR\ (Snow)$
Ambiguous	$\left(((1 - B_5)B_6 > 225)\ OR\ \left(\frac{B_4}{B_3} > 2\right)\ OR\ \left(\frac{B_4}{B_2} > 2\right)\ OR\ (Desert)\right)\ AND\ (\sim NotCloud)$
ColdCloud	$((1 - B_5)B_6 \geq 210)\ AND\ (\sim Ambiguous)\ AND\ (\sim NotCloud)$
WarmCloud	$((1 - B_5)B_6 < 210)\ AND\ (\sim Ambiguous)\ AND\ (\sim NotCloud)$

Classification Rules for Pass One

Williams, J.A., Dawood, A.S., Visser, S.J.: “FPGA-based Cloud Detection for Real-Time Onboard Remote Sensing”, Proceedings of IEEE International Conference on Field-Programmable Technology (FPT 2002), 16-18 Dec. 2002, pp.110 – 116

Landsat 7 ETM+ ACCA
(Algorithm Outline)

- **Pass Two**
  - Defines ambiguous clouds
    - Thermal properties of clouds identified during Pass One are characterized and used to identify remaining cloud pixels
    - Band 6 statistical moments (mean, standard deviation, skew, kurtosis) are computed for clouds identified during Pass One
    - The 95th percentile becomes the new thermal threshold for Pass Two
    - Image pixels that fall below the new thermal threshold and survive the first three Pass-One filters are classified as clouds

$$\eta = \frac{1}{n}\sum_{i=1}^{n} x_i \quad , \quad \sigma^2 = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \eta)^2$$

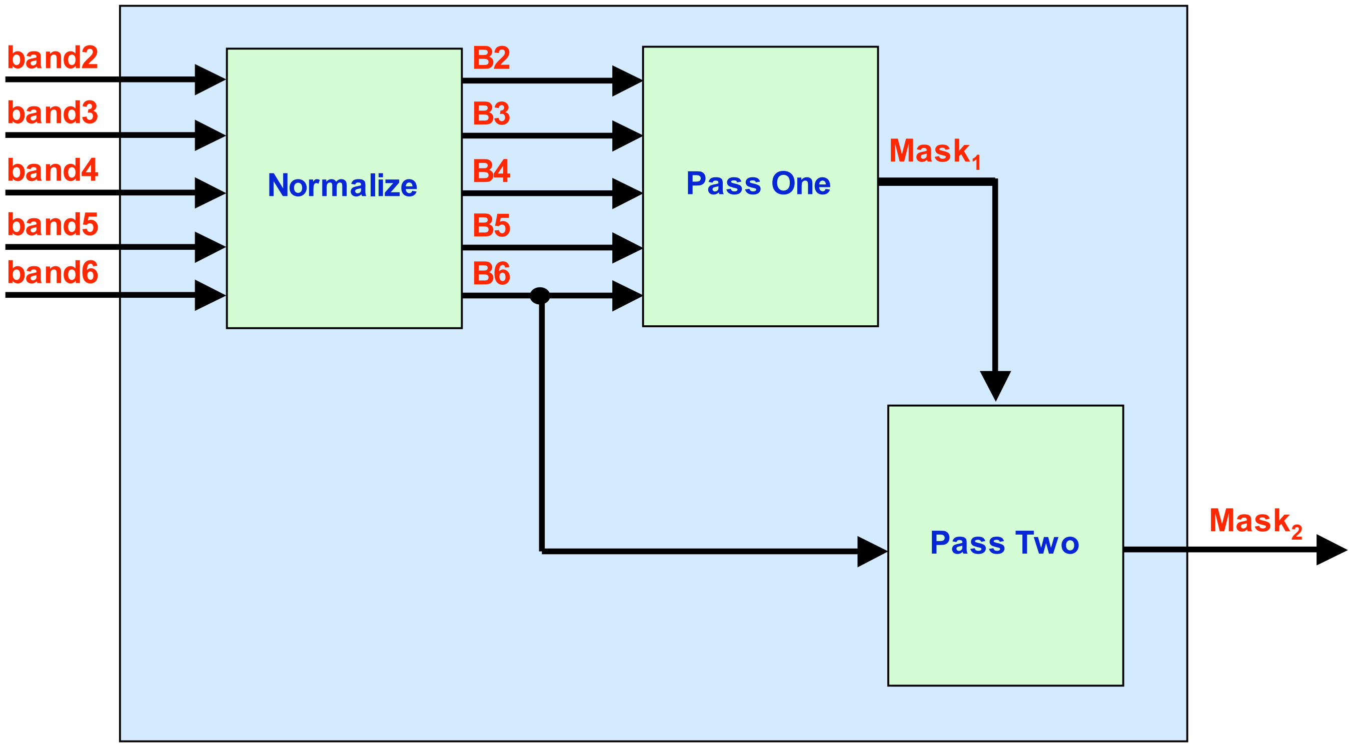
$$Skewness = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{x_i - \eta}{\sigma}\right)^3$$

$$Kurtosis = \frac{1}{n-3}\sum_{i=1}^{n}\left(\frac{x_i - \eta}{\sigma}\right)^4$$

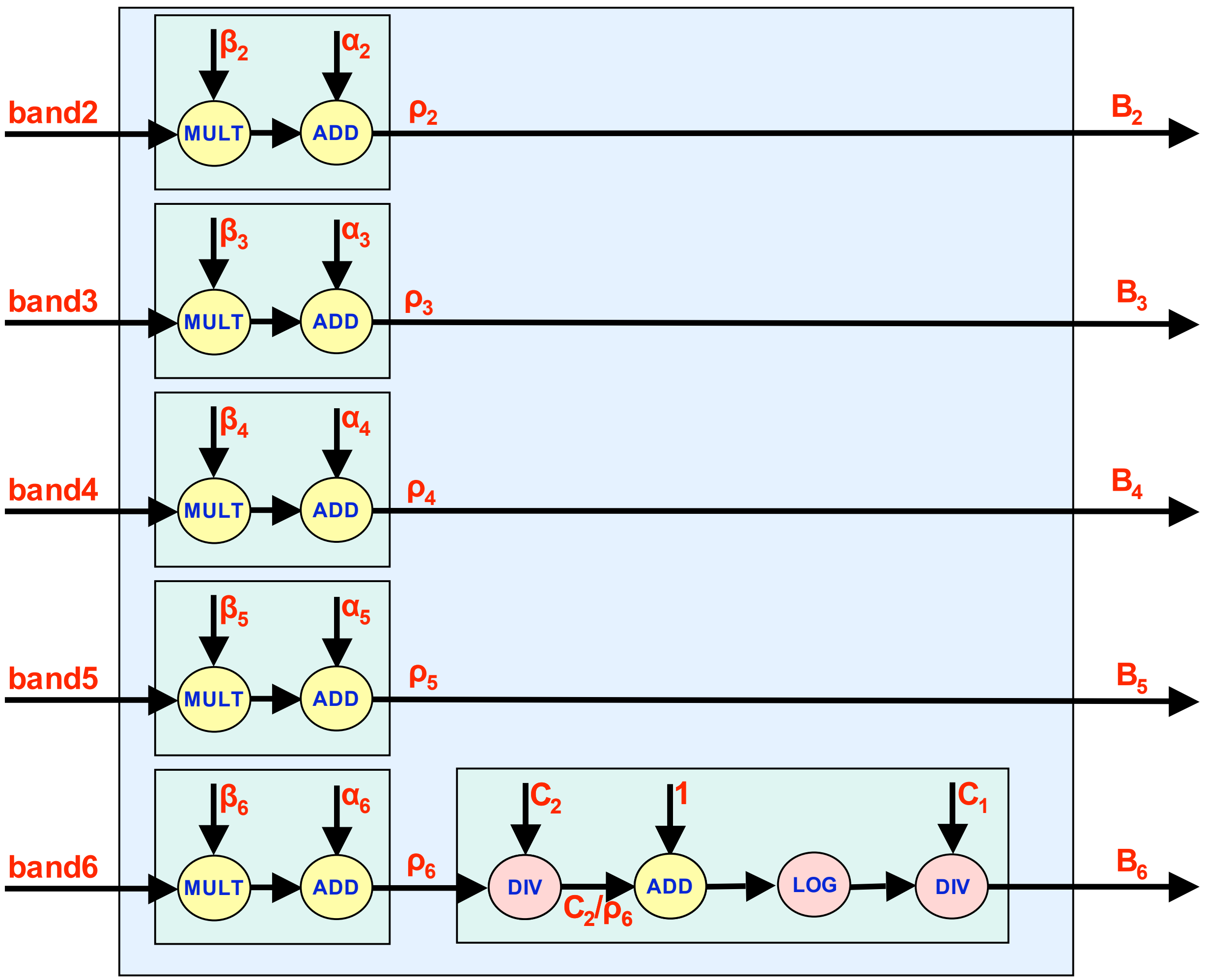
Outline

- Objectives
- Introduction and Background
  - Cloud Detection Theory
  - Cloud Detection Algorithms
- **Implementation Approach**
  - **Architectural Modules**
  - **Testbed (SRC-6)**
- Experimental Results
  - Measurements Scenarios
  - Detection Accuracy
  - Performance
- Concluding Remarks
- References

Top Hierarchy Module



Normalization Module

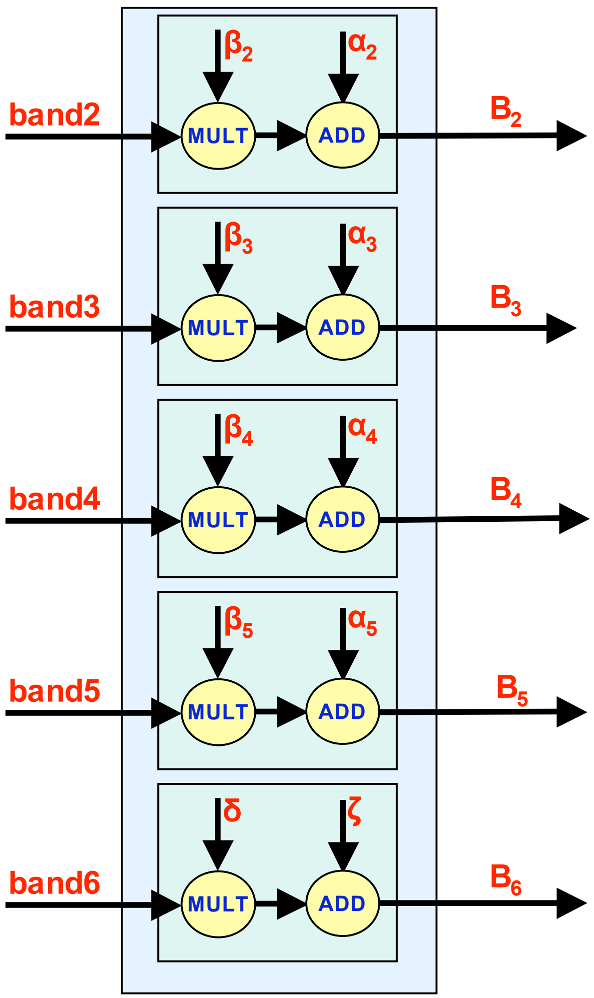


$$\rho_i = \beta_i \times band_i + \alpha_i \ , \ \ i = 2,3,4,5,6$$

$$B_i = \rho_i \ , \ \ i = 2,3,4,5$$

$$B_6 = \frac{C_1}{\log\left(\frac{C_2}{\rho_6} + 1\right)}$$

Approximated Normalization Module



$$\rho_i = \beta_i \times band_i + \alpha_i \ , \ i = 2,3,4,5,6$$

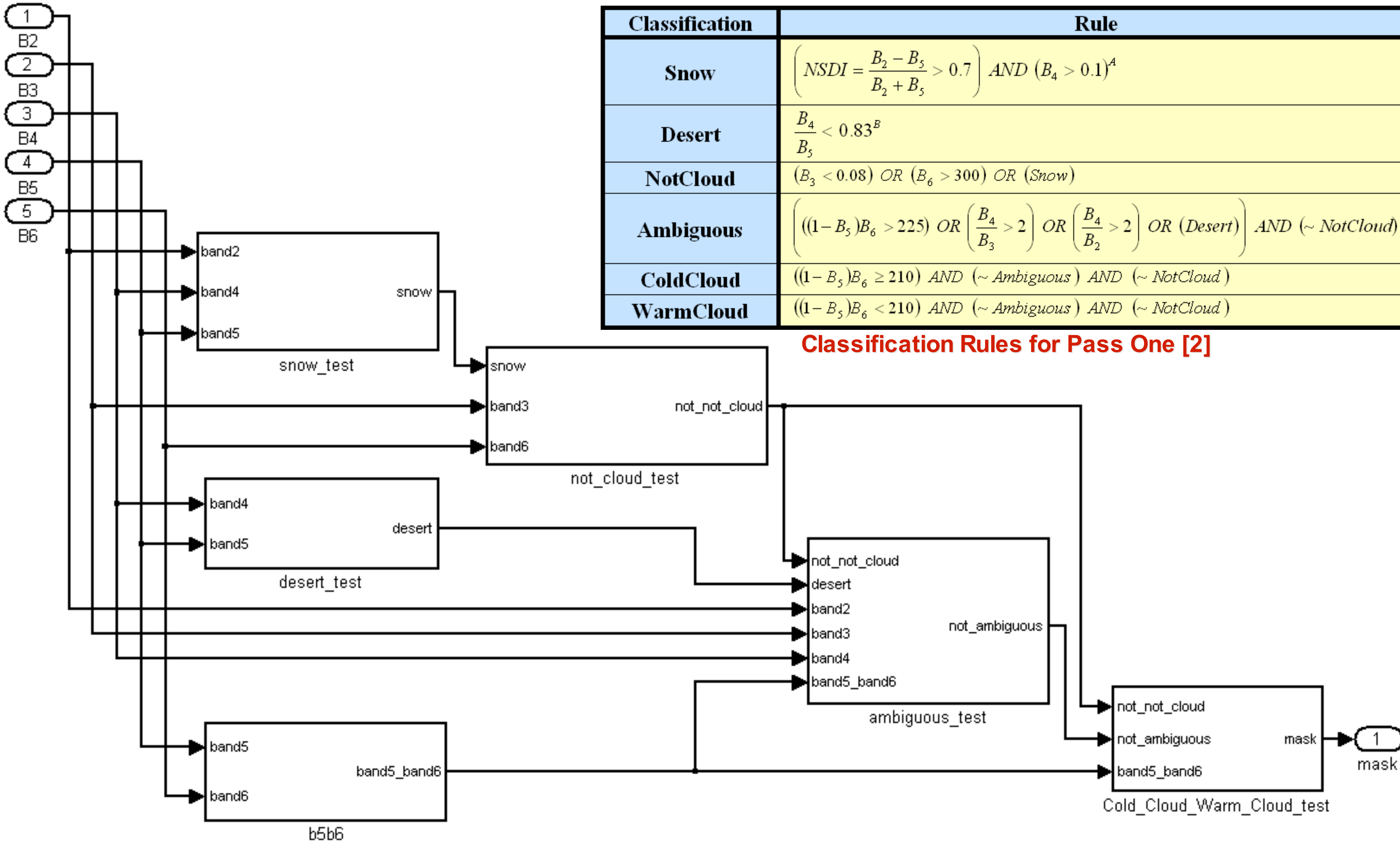
$$B_i = \rho_i \ , \ i = 2,3,4,5$$

$$B_6 = \frac{C_1}{\log\left(\frac{C_2}{\rho_6} + 1\right)} \cong \frac{C_1}{1 + \log(C_2)} + \frac{C_1\left(1 - \frac{1}{C_2}\right)}{(1 + \log(C_2))^2} \times \rho_6$$

$$B_6 \cong \frac{C_1 \cdot \alpha_6}{1 + \log(C_2)} + \frac{C_1\left(1 - \frac{1}{C_2}\right) \cdot \beta_6}{(1 + \log(C_2))^2} \times band_6$$

$$B_6 \cong \zeta + \delta \times band_6$$

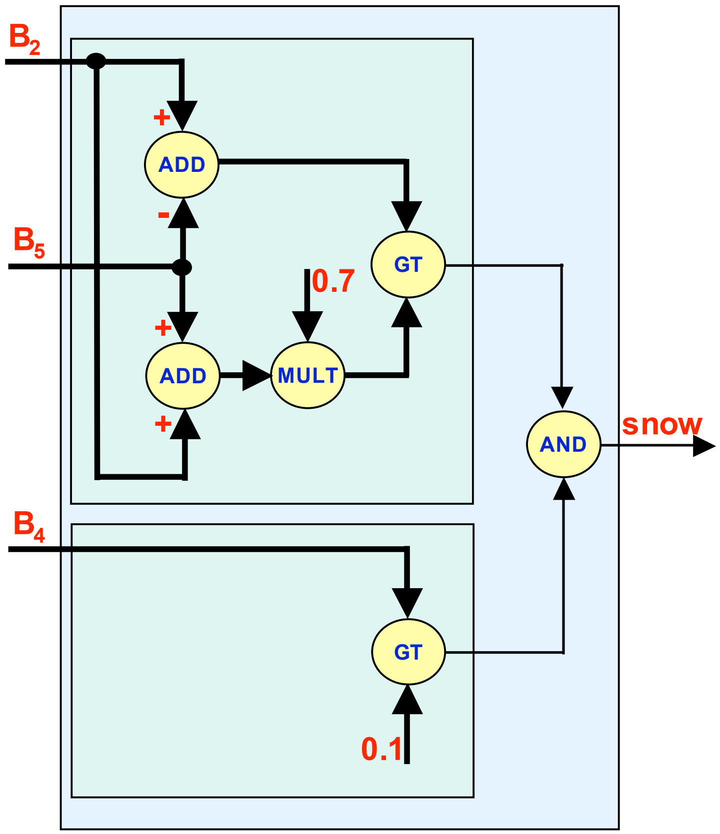
Pass-One Module



Classification	Rule
Snow	$\left(NSDI = \frac{B_2 - B_5}{B_2 + B_5} > 0.7\right)\ AND\ (B_4 > 0.1)^A$
Desert	$\frac{B_4}{B_5} < 0.83^B$
NotCloud	$(B_3 < 0.08)\ OR\ (B_6 > 300)\ OR\ (Snow)$
Ambiguous	$\left(((1-B_5)B_6 > 225)\ OR\ \left(\frac{B_4}{B_3} > 2\right)\ OR\ \left(\frac{B_4}{B_2} > 2\right)\ OR\ (Desert)\right)\ AND\ (\sim NotCloud)$
ColdCloud	$((1-B_5)B_6 \geq 210)\ AND\ (\sim Ambiguous)\ AND\ (\sim NotCloud)$
WarmCloud	$((1-B_5)B_6 < 210)\ AND\ (\sim Ambiguous)\ AND\ (\sim NotCloud)$

Classification Rules for Pass One [2]

Optimizing Hardware Resources Usage
(Algebraic Re-Formulation)

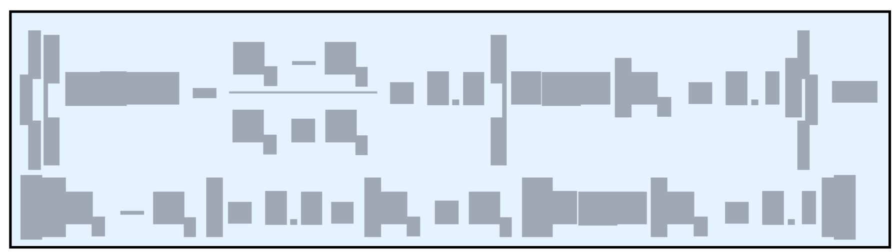


Snow-Test Module

Classification	Rule
Snow	$\left(NSDI = \frac{B_2 - B_5}{B_2 + B_5} > 0.7\right)$ AND $(B_4 > 0.1)^A$
Desert	$\frac{B_4}{B_5} < 0.83^B$
NotCloud	$(B_3 < 0.08)$ OR $(B_6 > 300)$ OR $(Snow)$
Ambiguous	$\left(((1 - B_5)B_6 > 225)\ OR\ \left(\frac{B_4}{B_3} > 2\right)\ OR\ \left(\frac{B_4}{B_2} > 2\right)\ OR\ (Desert)\right)$ AND $(\sim NotCloud)$
ColdCloud	$((1 - B_5)B_6 \geq 210)$ AND $(\sim Ambiguous)$ AND $(\sim NotCloud)$
WarmCloud	$((1 - B_5)B_6 < 210)$ AND $(\sim Ambiguous)$ AND $(\sim NotCloud)$

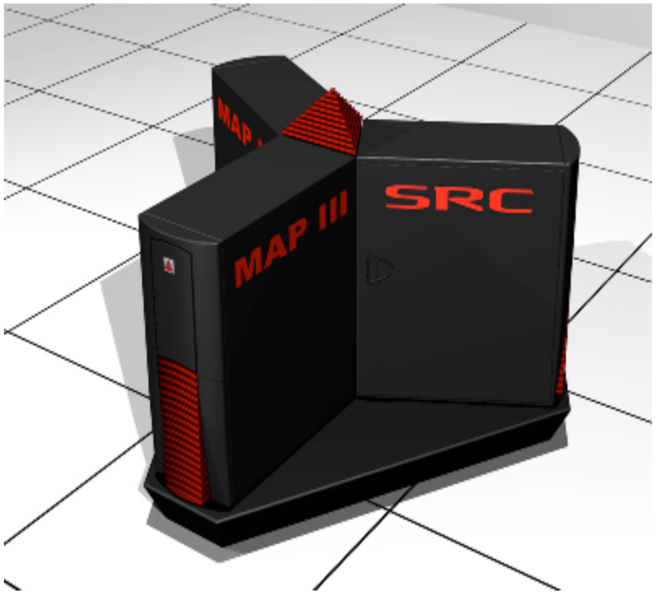
Classification Rules for Pass One [2]

Division Eliminated



SRC Systems

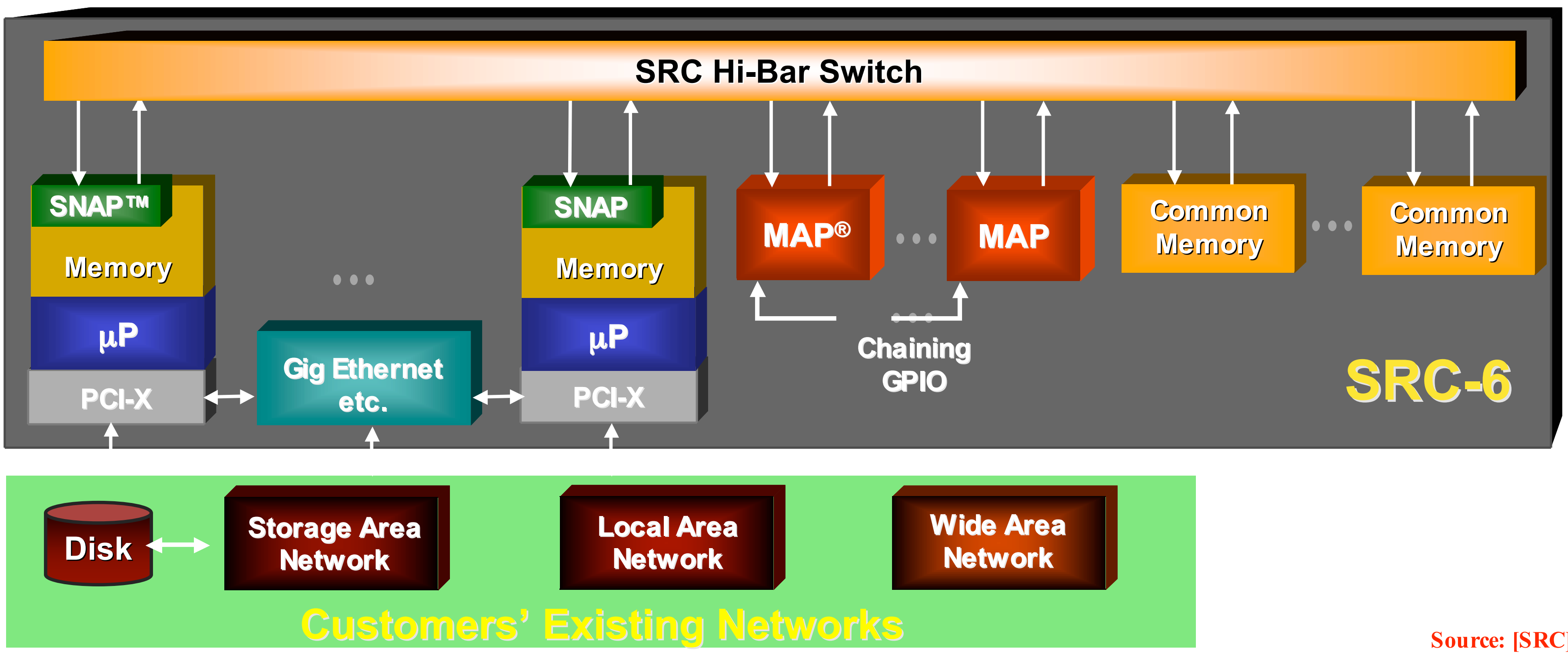
http://www.srccomp.com/



Source: [SRC, MAPLD04]

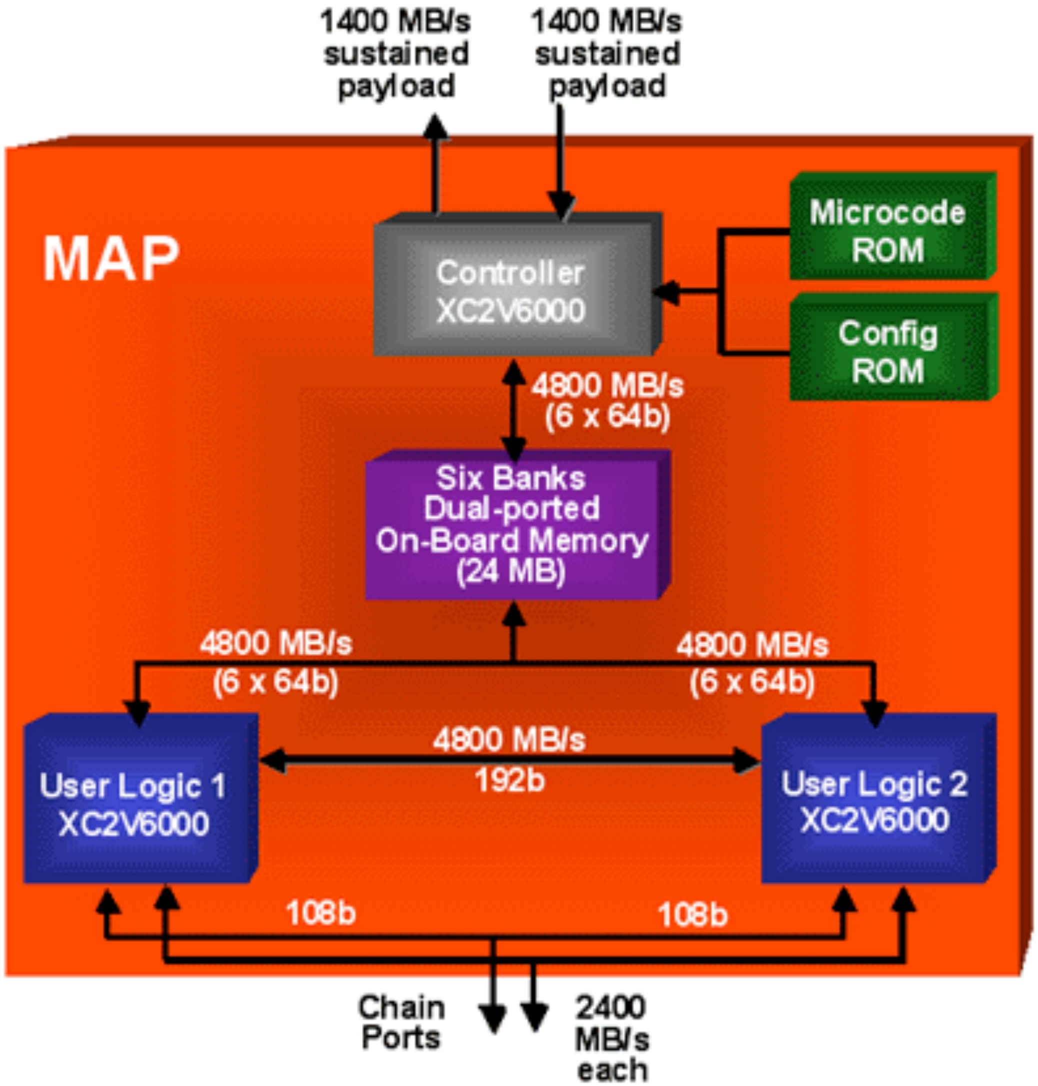
SRC Hi-Bar™ Based Systems

- Hi-Bar sustains 1.4 GB/s per port with 180 ns latency per tier
- Up to 256 input and 256 output ports with two tiers of switch
- Common Memory (CM) has controller with DMA capability
- Controller can perform other functions such as scatter/gather
- Up to 8 GB DDR SDRAM supported per CM node



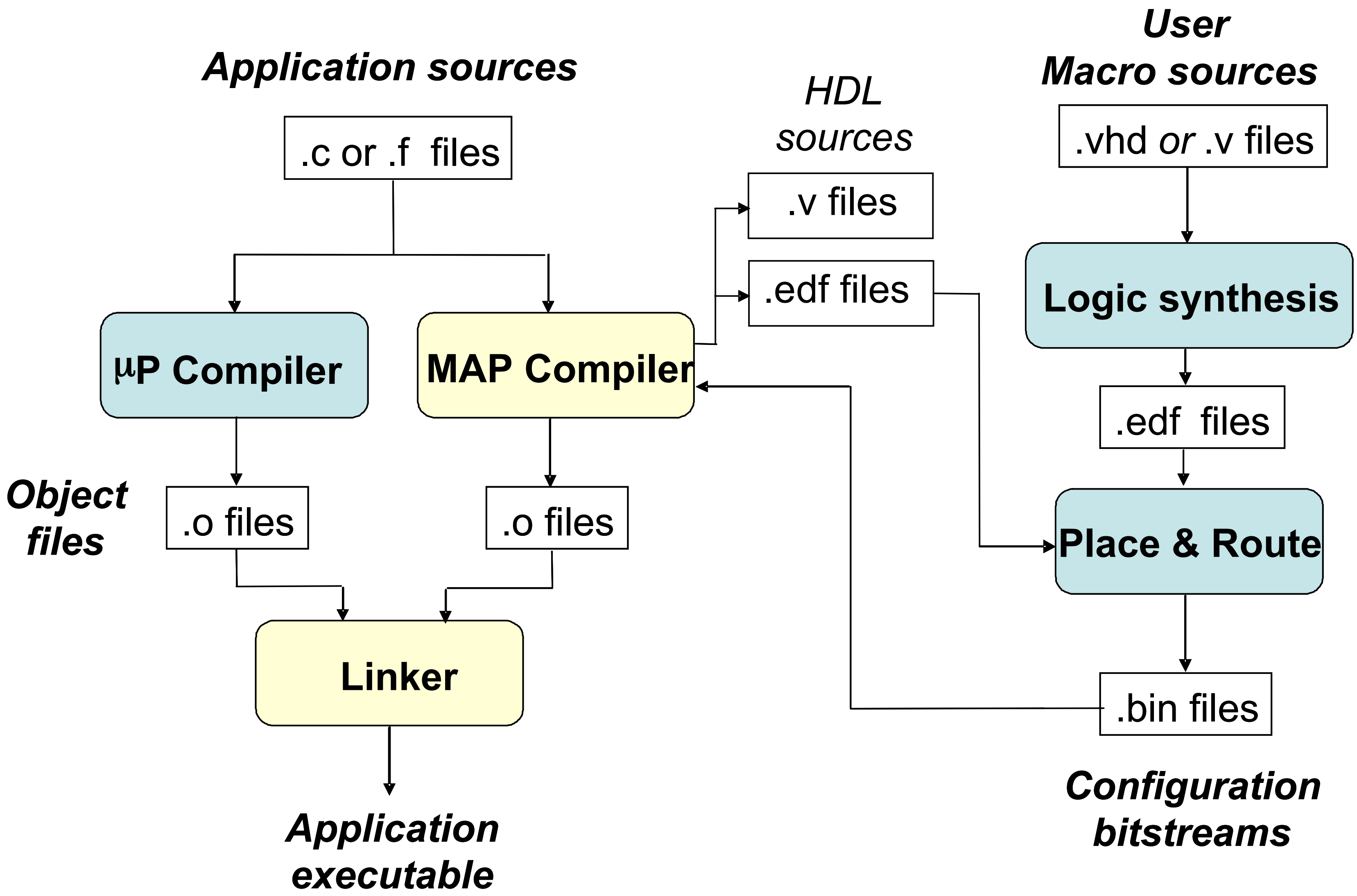
Source: [SRC]

SRC Reconfigurable Processor



Source: [SRC]

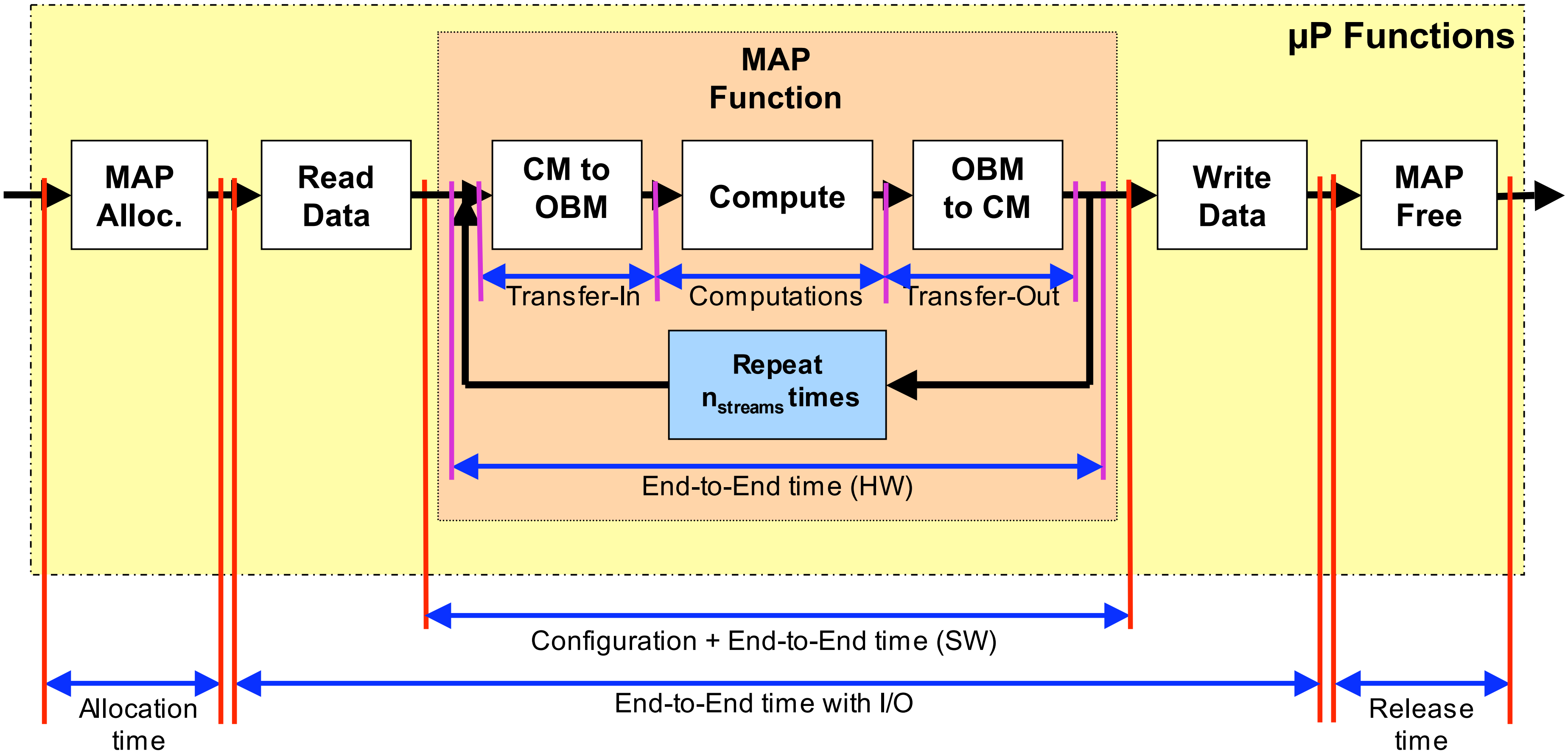
SRC Software Environment



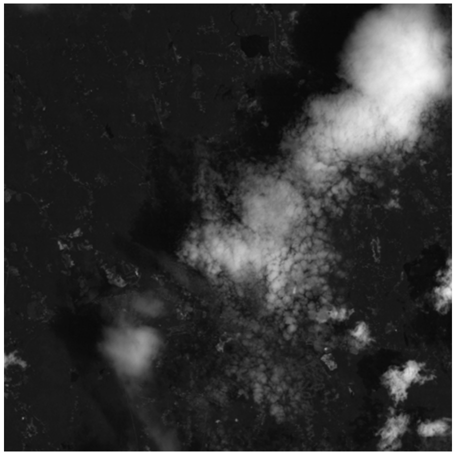
Outline

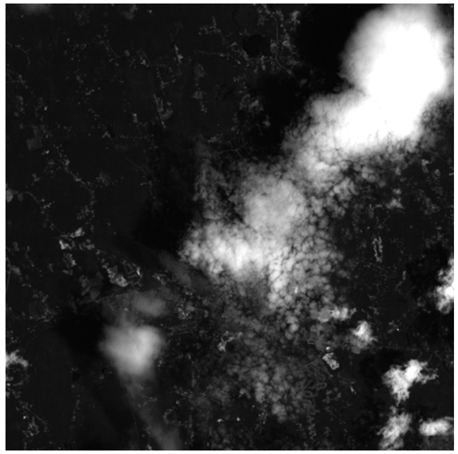
- Objectives
- Introduction and Background
  - Cloud Detection Theory
  - Cloud Detection Algorithms
- Implementation Approach
  - Architectural Modules
  - Testbed (SRC-6)
- **Experimental Results**
  - **Measurements Scenarios**
  - **Detection Accuracy**
  - **Performance**
- Concluding Remarks
- References

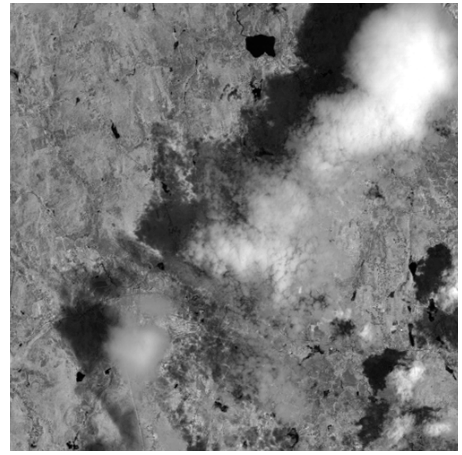
Measurements Scenarios

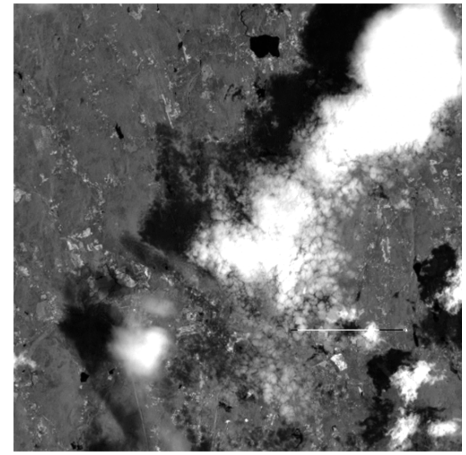


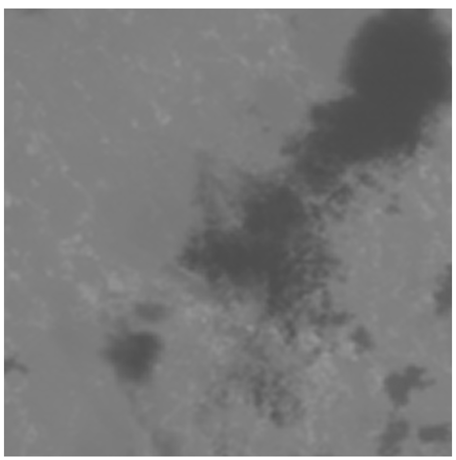
Detection Accuracy
(Software/Reference Mask, Hardware Masks)

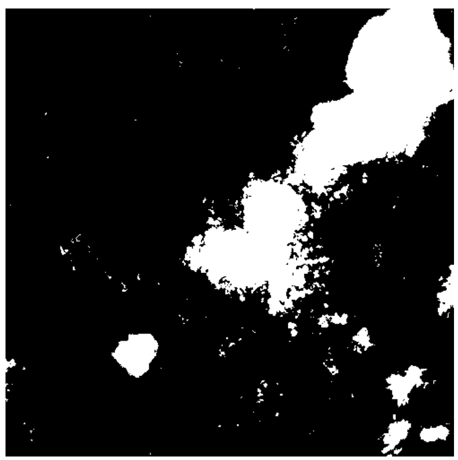

Band 2 (Green Band)

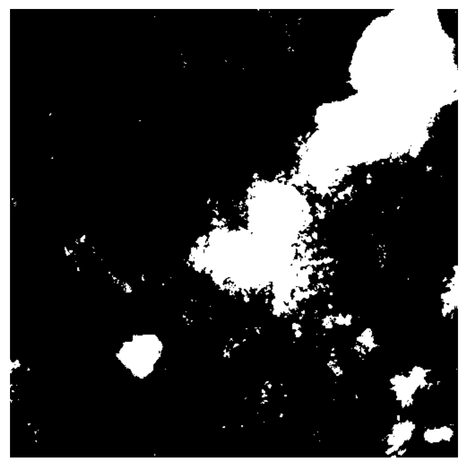

Band 3 (Red Band)

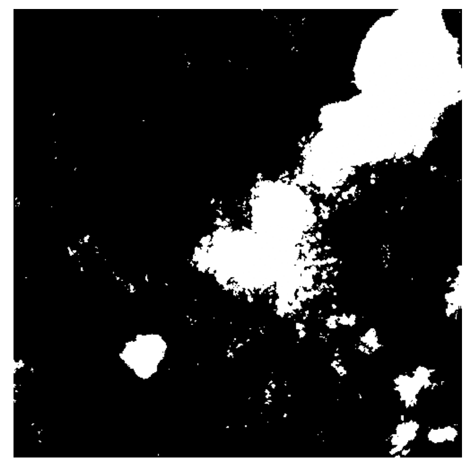

Band 4 (Near-IR Band)


Band 5 (Mid-IR Band)


Band 6 (Thermal IR Band)


Software/Reference Mask


Hardware Floating-Point Mask (Approximate Normalization)

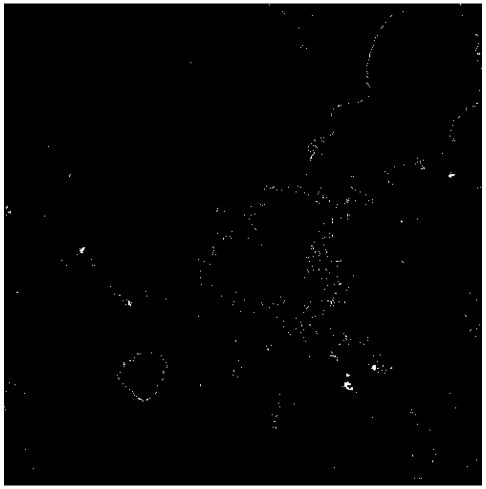

Hardware Fixed-Point Mask (Approximate Normalization)

Detection Accuracy (cnt'd)
(Approximate Normalization and Quantization Errors)

Approximation Error
(0.1028 %)

Hardware Floating-Point Error
(0.1028 %)

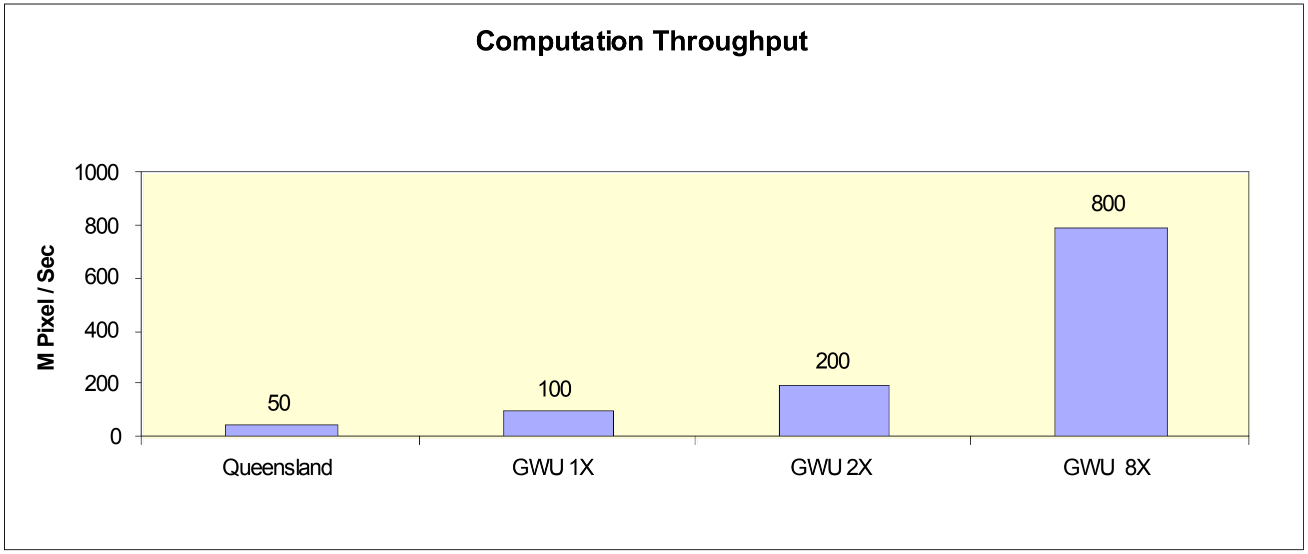
Reported Error (1.02 %)
by Williams et al. [2]

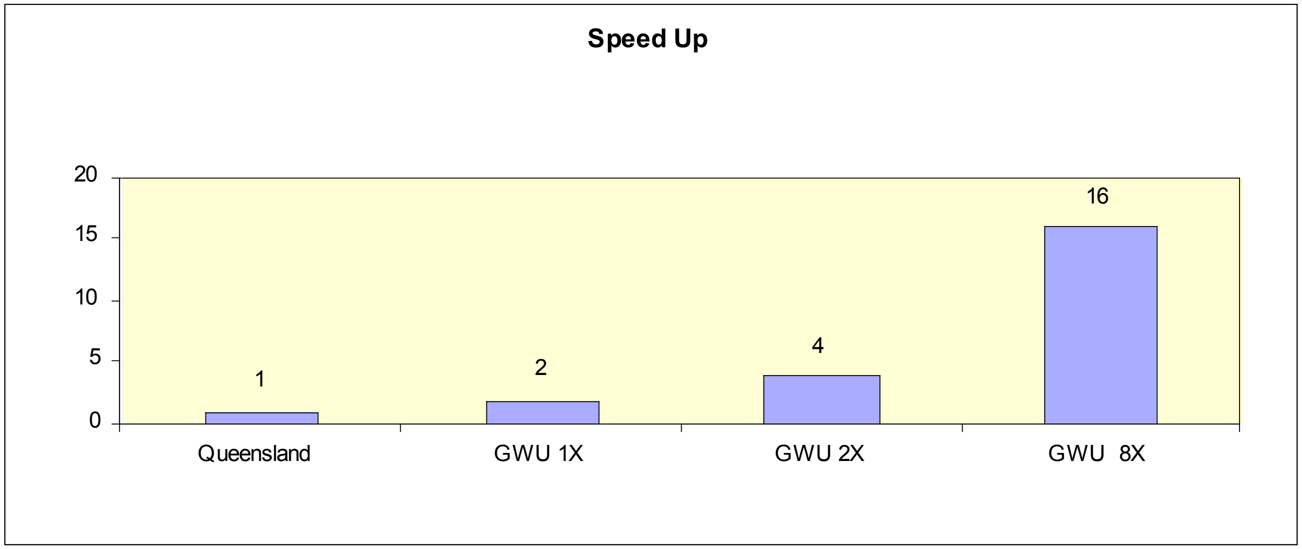


Hardware Fixed-Point (12-bit) Error
(0.2676 %)

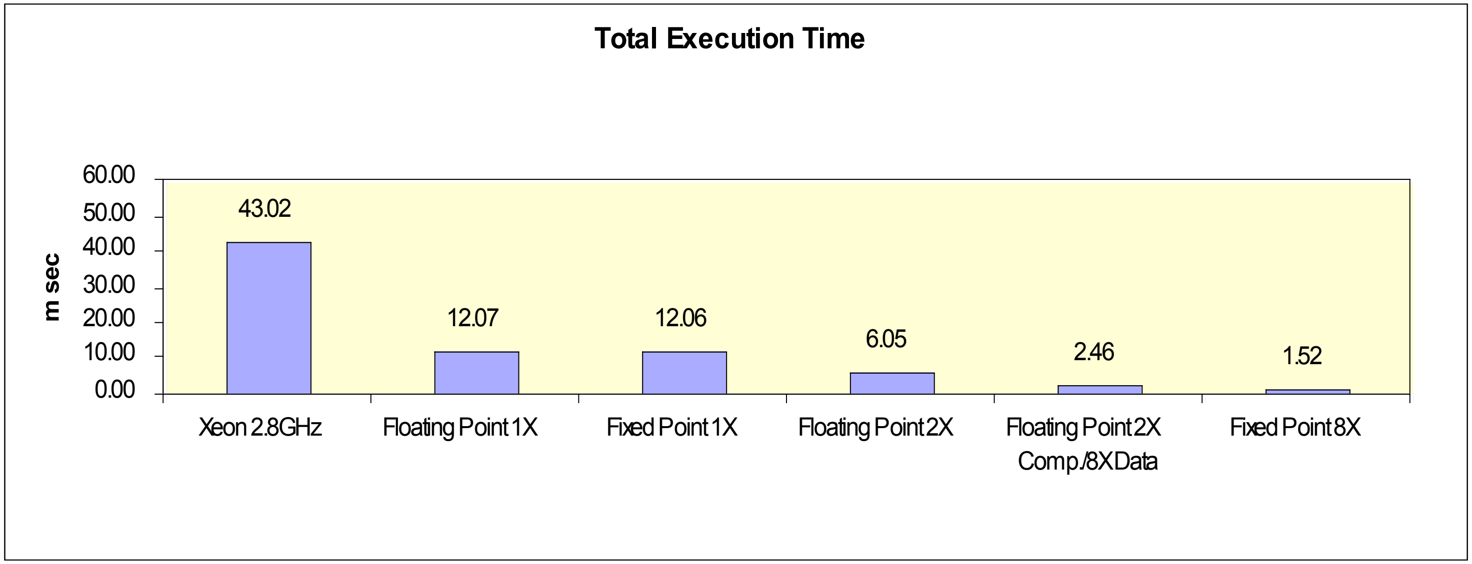
Hardware Fixed-Point (23-bit) Error
(0.1028 %)

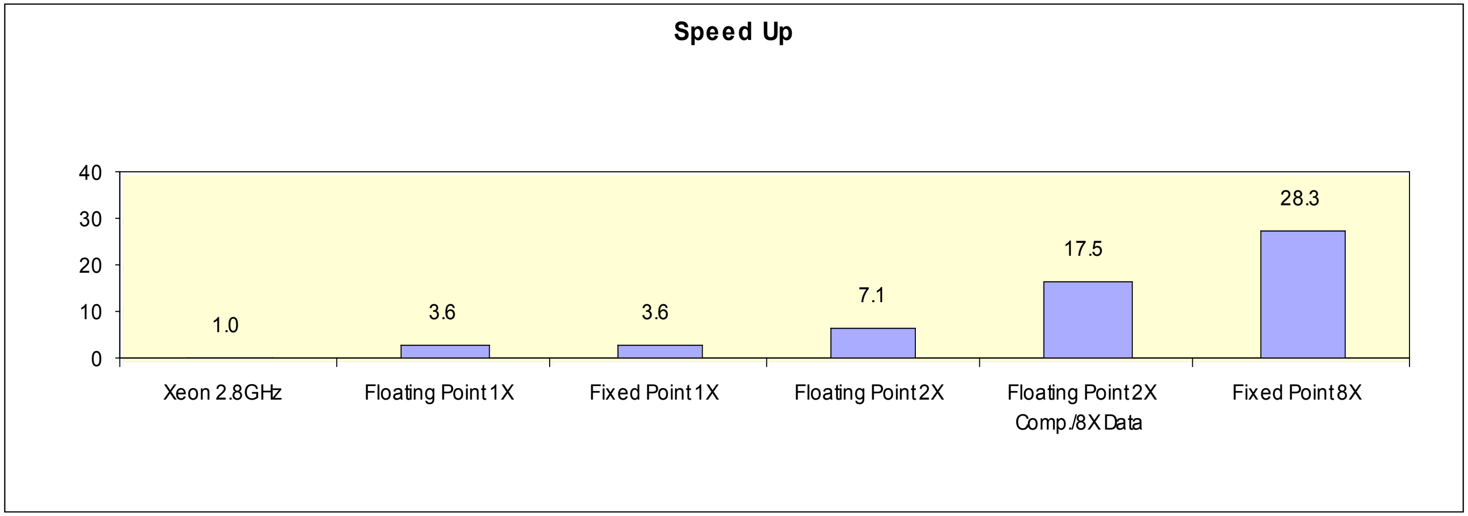
Hardware Computation Throughput
(Hardware-to-Hardware Performance)





SRC-6 vs. Intel Xeon 2.8 GHz
(Hardware-to-Software Performance)





Concluding Remarks

- The Automatic Cloud Cover Assessment (ACCA) algorithm is prototyped on a reconfigurable architecture
- The prototype is characterized by:
  - Implementation Completeness
    - Normalization
    - Pass-one
    - *Pass-two (not implemented due to time constraints)*
  - Higher Detection Accuracy
    - Zero quantization errors through the floating-point and full-precision fixed-point implementations
    - 9.8x higher accuracy compared to previous hardware implementations
  - Higher Performance
    - 16x speedup over previous hardware implementations
    - 28x speedup over microprocessor implementations

References

[1] Basso, R.S., Le Moigne, J., Veuella, S., and Irish, R.R.: FPGA Implementation for On-Board Cloud Detection, International Geoscience and Remote Sensing Symposium. Hawaii, 20-24 July 2000

[2] Williams, J.A., Dawood, A.S., Visser, S.J.: FPGA-based Cloud Detection for Real-Time Onboard Remote Sensing, Poceedings of IEEE International Conference on Field-Programmable Technology (FPT 2002), 16-18 Dec. 2002, pp.110 – 116

[3] El-Araby, E., Taher, M., Gaj, K., El-Ghazawi, T., Caliga, D., Alexandridis, N.: System-Level Parallelism and Throughput Optimization in Designing Reconfigurable Computing Applications. Reconfigurable Architectures Workshop, RAW 2004, Proc. International Parallel and Distributed Processing Symposium (IPDPS) Workshops 2004, Santa Fe, New Mexico, USA, April 2004

[4] Fidanci, O.D., Poznanovic, D., Gaj, K., El-Ghazawi, T., Alexandridis, N.: Performance and Overhead in a Hybrid Reconfigurable Computer. Reconfigurable Architectures Workshop, RAW 2002, Proc. International Parallel and Distributed Processing Symposium (IPDPS) Workshops 2003, Nice, France, April 2003, pp.176-183

[5] SRC-6 C-Programming Environment Guide, SRC Computers, Inc. 2004